Evapotranspiration and Droughts

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SIGNIFICANCE OF EVAPOTRANSPIRATION

Apart from precipitation, the most significant component of the hydrologic budget is evapotranspiration. Evapotranspiration varies regionally and seasonally; during a drought it varies according to weather and wind conditions. Because of these variabilities, water managers who are responsible for planning and adjudicating the distribution of water resources need to have a thorough understanding of the evapotranspiration process and knowledge about the spatial and temporal rates of evapotranspiration.

Estimates of average statewide evapotranspiration for the conterminous United States range from about 40 percent of the average annual precipitation in the Northwest and Northeast to about 100 percent in the Southwest. During a drought, the significance of evapotranspiration is magnified, because evapotranspiration continues to deplete the limited remaining water supplies in lakes and streams and the soil.

The lower 5 miles of the atmosphere transports an average of about 40,000 billion gallons of water vapor over the conterminous United States each day (U.S. Geological Survey, 1984). Slightly more than 10 percent of this moisture, however, is precipitated as rain, sleet, hail, or snow. The disposition of this precipitation in the conterminous United States is illustrated in **figure 1**. As shown, the greatest proportion, about 67 percent, returns to the atmosphere through evapotranspiration, about 29 percent is discharged from the conterminous United States as net surface-water outflow into the Pacific and Atlantic Oceans and across the borders into Canada and Mexico, about 2 percent is discharged as ground-water outflow, and about 2 percent is consumed by people, animals, plants, and industrial and commercial processes (U.S. Geological Survey, 1990). For most of the United States, evaporation returns less moisture to the atmosphere than does transpiration.

EVAPOTRANSPIRATION PROCESS

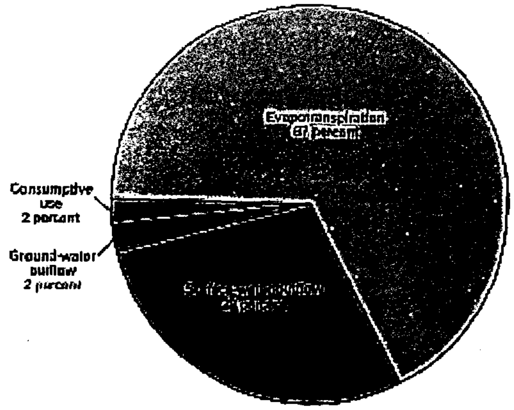

Figure 1. Average disposition of 4200 billion gallons per day of precipitation in the conterminous United States. (source: Data from U.S. Geological Survey, 1990).

Evapotranspiration is the water lost to the atmosphere by two processes-evaporation and transpiration. Evaporation is the loss from open bodies of water, such as lakes and reservoirs, wetlands, bare soil, and snow cover; transpiration is the loss from living-plant surfaces. Several factors other than the physical characteristics of the water, soil, snow, and plant surface also affect the evapotranspiration process. The more important factors include net solar radiation, surface area of open bodies of water, wind speed, density and type of vegetative cover, availability of soil moisture, root depth, reflective land-surface characteristics, and season of year.

Assuming that moisture is available, evapotranspiration is dependent primarily on the solar energy available to vaporize the water. Because of the importance of solar energy, evapotranspiration also varies with latitude, season of year, time of day, and cloud cover. The distribution of mean daily solar radiation for the United States **(fig. 2)** shows a regional variation similar to that of mean annual lake evaporation **(fig. 3)** and mean annual air temperature. The areas that receive the maximum solar radiation and have the greatest lake evaporation in the conterminous United States are in the Southwest; the areas that receive the minimum solar radiation and have the least lake evaporation are in the Northeast and Northwest. According to the 1980 Bureau of Census data (U.S. Bureau of the Census, 1987, p. 181), the area of open-water bodies in the 48 conterminous States totals 38.4 million acres. Mean annual lake evaporation ranges from about 20 inches in parts of Maine, Oregon, and Washington to about 80 inches in parts of Arizona, California, and Nevada.

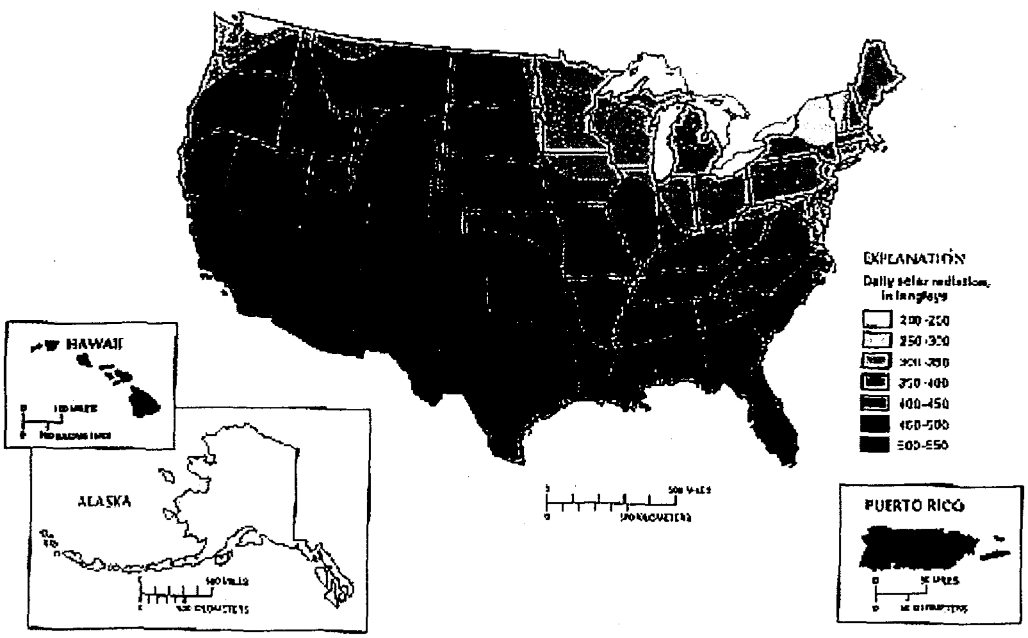

Figure 2. Mean daily solar radiation in the United States and Puerto Rico.(Source: Data from the

U.S. Department of Commerce, 1968).

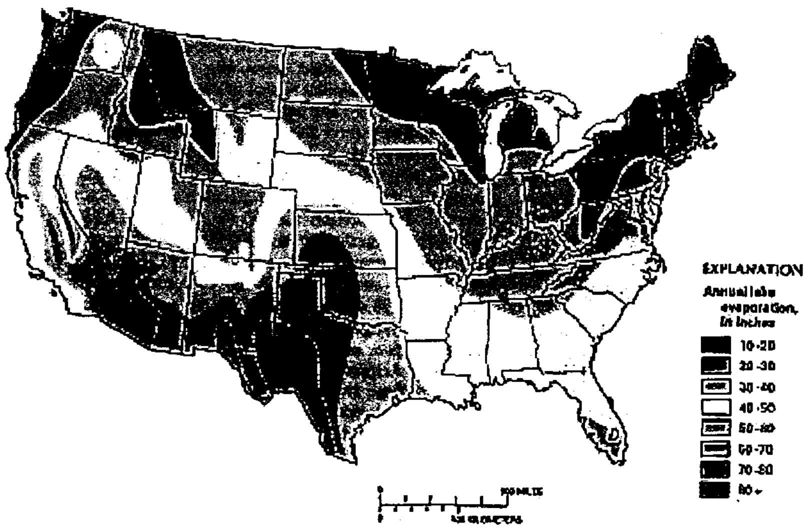

Figure 3. *Mean annual lake evaporation in the conterminous United States, 1946-55. Data not available for Alaska, Hawaii, and Puerto Rico.* (Source: Data from U.S. Department of Commerce, 1968).

Another important climatic factor that contributes to evapotranspiration is wind speed. Winds affect evapotranspiration by bringing heat energy into an area and removing the vaporized moisture. A 5-mile-per-hour wind will increase still-air evapotranspiration by 20 percent; a 15-mile-per-hour wind will increase still-air evapotranspiration by 50 percent (Chow, 1964, p. 6-20). Maximum mean annual wind velocities, averaging more than 14 miles per hour, are recorded in the central United States. Minimum mean annual wind velocities, averaging less than 8 miles per hour, are recorded along the West Coast and in the mountainous part of the east-central United States (Eagleman, 1976, p. 4).

The type of vegetative cover is not as important in the evapotranspiration process as is solar radiation if the vegetative cover is dense and sufficient soil moisture is available (Kozlowski, 1964, p. 147). Most plants that have a shallow root system, however, will experience moisture stress, which results in decreased transpiration during prolonged droughts.

The reflective characteristics of the land surface also have an effect on the magnitude of evapotranspiration. Coniferous forests and alfalfa fields reflect only about 25 percent of the solar energy, thus retaining substantial thermal energy to promote transpiration; in contrast, deserts reflect as much as 50 percent of the solar energy, depending on the density of vegetation (Rosenberg, 1986, p. 13).

The seasonal trend of evapotranspiration within a given climatic region follows the seasonal trend of solar radiation and air temperature. Minimum evapotranspiration rates generally occur during the coldest months of the year; maximum rates, which generally coincide with the summer season, when water may be in short supply, also depend on the availability of soil moisture and plant maturity. However, the seasonal maximum evapotranspiration actually may precede or follow the seasonal maximum solar radiation and air temperature by several weeks.

REGIONAL AND SEASONAL VARIABILITY OF EVAPOTRANSPIRATION

The United States is covered by a variety of vegetation due mostly to the variability in climate and soil types across the country. In the conterminous United States, two major forested areas exist: the eastern forests, which include large areas of conifers and hard- woods, extend from the East Coast to the eastern edge of the central Great Plains; the western forests, which are predominantly conifers that grow in mountainous areas separated by semiarid basins, extend from the West Coast to the western edge of the central Great Plains. The forests of the eastern United States cover 385 million acres; those of the western United States cover 353 million acres and include about 24 million acres in Alaska (U.S. Department of Agriculture, 1987, p. 475). Estimates of evapotranspiration for the eastern forests range from slightly less than 12 inches per year for spruce-fir forests to slightly more than 36 inches per year for pines and river-bottom hardwoods and for the western forests from about 6 inches per year for pinyon and juniper forests to almost 60 inches per year for Pacific Douglas-fir forests (Kittredge, 1948).

Some of the greatest users of water are phreatophytes, which are plants characterized by a deep root system that extends to or near the water table. Saltcedar, which is a particularly aggressive phreatophyte, is estimated to cover 16 million acres in the flood plains of the 17 Western States; it thrives in the arid regions south of the 37th parallel and below an altitude of 5,000 feet in the Southwestern States (Robinson, 1958, p. 75). Mean annual evapotranspiration by this phreatophyte was estimated to be about 56 inches for areas of dense cover along the flood plain of the Gila River in south-central Arizona (Culler and others, 1982).

In contrast to the two major forest areas, the central Great Plains are characterized by large regions of rangeland and cropland (irrigated and nonirrigated). The total rangeland in the conterminous United States and Alaska is about 817 million acres, and the total cropland is about 427 million acres (U.S. Department of Agriculture, 1987). Within these areas, irrigated grass or croplands occupy about 60 million acres (Irrigation Journal, 1985). The average annual evapotranspiration for irrigated lands varies greatly and, apart from the climatic controls, is dependent on the grass or crop type, quantity of water applied, and length of the growing season. During a drought, natural vegetation may experience moisture stress and wilting, whereas irrigated grasses and crops continue to grow and transpire at a normal rate (if water supplies are available for irrigation).

Most estimates of evapotranspiration are derived from studies of small areas (a few acres or less) where climate, available moisture, and plant cover are relatively uniform; thus, regional estimates are uncommon. However, the magnitude and distribution of mean annual evapotranspiration for regions of the United States have been estimated from hydrologic budgets given for each State in the 1987 *National Water Summary* (U.S. Geological Survey, 1990), as shown in **figure 4**. The estimated mean annual evapotranspiration for each State was determined from the mean annual statewide values of four principal components of the hydrologic budget-precipitation, surface-water inflow, surface-water outflow, and consumptive use. All four components were measured or estimated, and evapotranspiration was computed as a residual of these components.

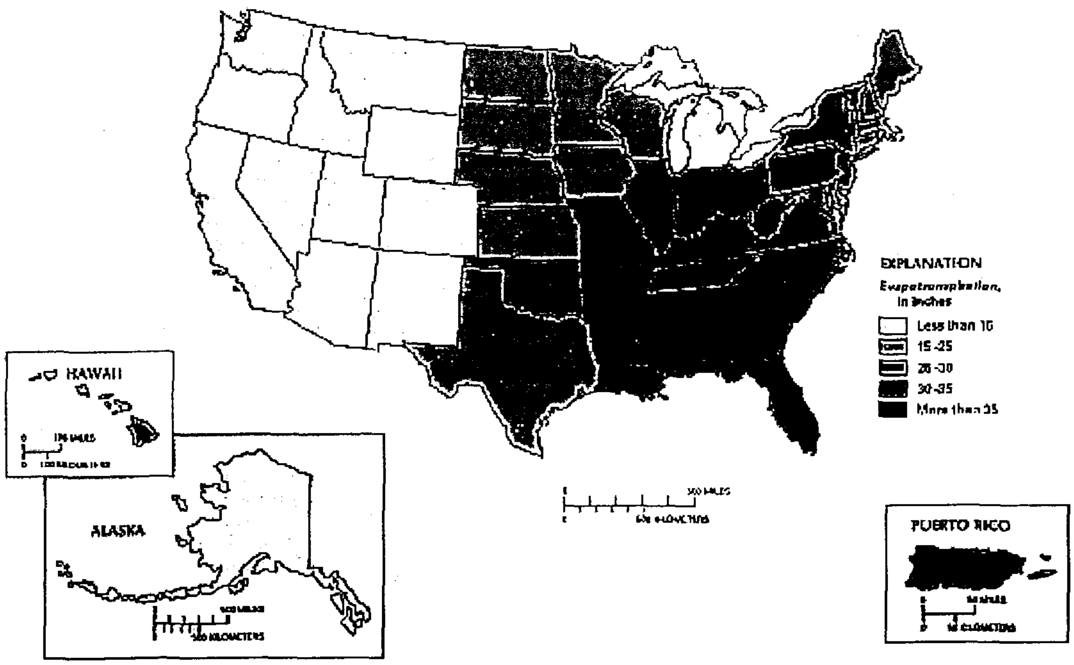

Figure 4. *Estimated mean annual evapotranspiration in the United States and Puerto Rico.* (Source:Data compiled from U.S. Geological Survey, 1990).

For the United States and Puerto Rico, the estimated mean annual evapotranspiration ranges from a maximum of 45 inches per year in Puerto Rico to a minimum of 7.6 inches per year in Alaska. Within the conterminous United States, the estimated mean annual evapotranspiration is greatest in the Southeast (about 35 inches per year or about 70 percent of the precipitation), which is an area of abundant precipitation, permeable soils, and substantial solar radiation; it is least in the semiarid region of the Southwest where precipitation is limited. For large areas of the Southwest, evapotranspiration is virtually equal to 100 percent of the precipitation, which is only about 10 inches per year. The ratio of estimated mean annual evapotranspiration to precipitation is least in the mountains of the Pacific Northwest and New England where evapotranspiration is about 40 percent of the precipitation.

The seasonal variability in evapotranspiration differs greatly throughout the United States and is similar to the seasonal trend in air temperature. In the northern part of the United States, measurable evapotranspiration, primarily transpiration by natural vegetation, usually begins in April, reaches a maximum in July, and decreases in October. In contrast, in the southern parts of the United States, evapotranspiration continues throughout the winter months, even though comparatively small, and generally is greatest in the early summer to midsummer months (June and July), when the leaf area of plants is fully developed.

Daily fluctuations in evapotranspiration also occur. On clear days, the rate of transpiration increases rapidly in the morning and reaches a maximum usually in early afternoon or midafternoon. The midday warmth can cause closure of plant stomata, which results in a decrease in transpiration (Kozlowski, 1964, p. 143).

Since the early 1970's, satellites orbiting the Earth have been used to monitor the vigor of vegetation. This information has been applied in the measurement of evapotranspiration, vegetative stress, and drought severity on a regional scale. In 1982, the National Oceanic and Atmospheric Administration

5

(NOAA), by using data from polar orbiting satellites, began weekly production of global maps that show visible and near-infrared data for the surface of the Earth. The instrument used to record these data is an Advanced Very High Resolution Radiometer, which scans the surface of the Earth continuously at a ground resolution covering an area of about 0.36 square mile. These data provide a measure of the spectral reflectance of the chlorophyll pigment in plants in the visible and near-infrared bands of the electromagnetic spectrum.

Mathematical expressions have been developed that combine the visible and near-infrared reflectance to provide a normalized-difference vegetation index of plant vigor (Tarpley and others, 1984). A large index value corresponds to areas of substantial evapotranspiration rates, which represent dense vegetative cover, permeable soils, and substantial soil moisture. A small index value corresponds to areas having minimal evapotranspiration, which represent bare ground or little vegetation, relatively impermeable soils, and minimal soil moisture. Because the vegetation-index data characterize the emissive and reflective properties of the landscape, the data potentially are useful in monitoring vegetation conditions associated with the spatial and temporal persistence of droughts that affect large areas.

An image of these indices provided by the U.S. Geological Survey is shown in **figure 5**. The image represents the mean of 43 weekly images collected by the NOAA-9 satellite from February through November 1987. The map shows variations in "greenness" that relate directly to variations in density of vegetative cover, plant vigor, and the seasonal duration of vegetative growth. Large index values (0.26 and larger) are displayed for the densely forested areas throughout much of the eastern, south-central, and extreme western parts of the United States. Except for the West Coast, the densely forested areas in the western part of the United States display index values generally less than 0.26, which may be attributed to the short growing season.

Agricultural regions, such as the Corn Belt area of the Midwest, display smaller index values (0.21 to 0.25) than the native vegetation regions of the Eastern States because the agricultural growing season is shorter than that of the native vegetation. Thus, the seasonal potential for evapotranspiration in agricultural areas would be expected to be distinctly less than that of the native vegetation (K.P. Gallo, National Oceanic and Atmospheric Administration, written commun., 1988).

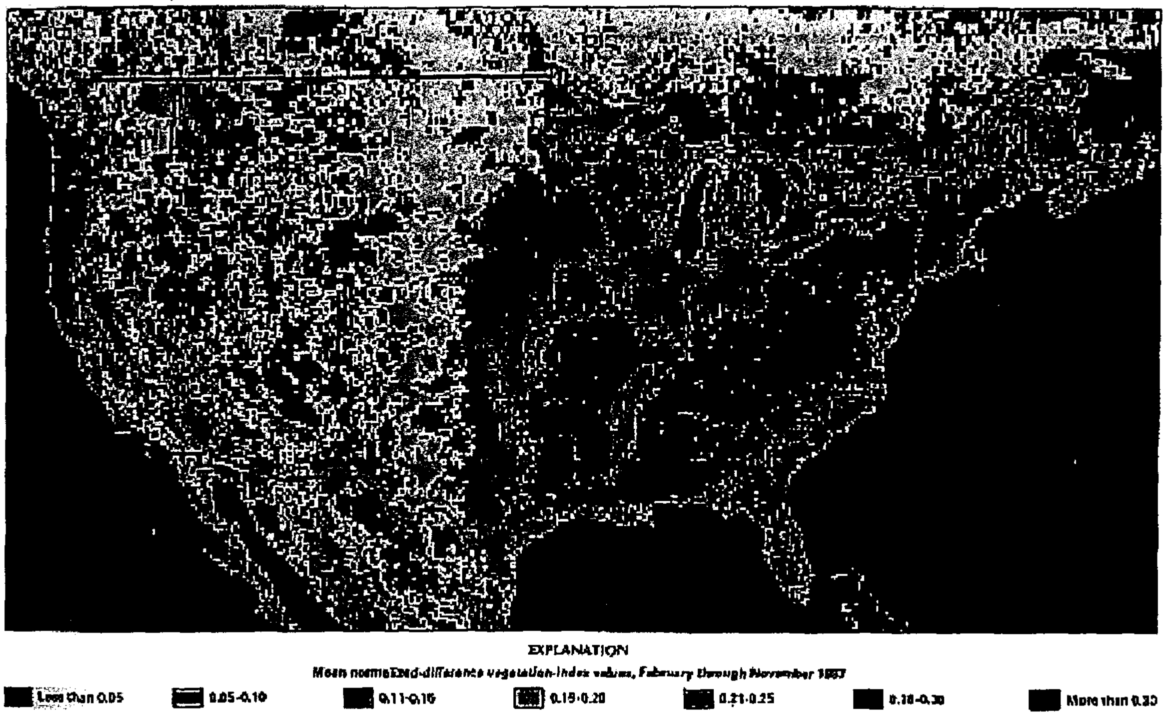

Figure 5. Mean normalized-difference vegetation-index values for the conterminous United States. Map produced from 43 weekly images acquired from February through November 1987 by the NOAA-9 polar-orbiting satellite using an Advanced Very High Resolution Radiometer. (Sources: Data from the National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite Data and Information Services; map from U.S. Geological Survey, Earth Resources Observation System Data Center).

CHANGE IN EVAPOTRANSPIRATION DURING A DROUGHT

Changes in evaporation and transpiration during a drought depend on the availability of moisture at the onset of a drought and the severity and duration of a drought. Also, weather conditions during a drought commonly include below-normal cloud cover and humidity and above-normal wind speed. These factors will increase the rate of evaporation from open bodies of water and from the soil surface, if soil moisture is available.

During a drought, transpiration by plants may decrease, as plants attempt to conserve water. The magnitude of the decrease in transpiration depends on the plant's root and leaf characteristics. The decrease in transpiration by phreatophytes, such as saltcedar, cottonwoods, bermuda grass, and alfalfa, typically is slight because they are deep rooted and obtain their water from near the water table rather than from the overlying soil zone. For example, alfalfa roots have been traced to a depth of 66 feet and also have been observed in a mine shaft at a depth of about 100 feet (Meinzer, 1927, p. 55). The decrease in transpiration by plants, such as cacti, in desert regions typically is slight because the plants have extensive root systems that obtain water from a large area and because their thick, fleshy leaves naturally transpire little water. In more humid areas having deciduous trees, some species of these trees decrease transpiration during droughts by leaf curling or leaf shedding (Kozlowski, 1964). The decrease in transpiration during droughts generally is greater in agricultural areas because crops die or their foliage (and, therefore, their ability to transpire water) is severely stunted during prolonged droughts.

SUMMARY

Apart from precipitation, evapotranspiration is the major component in the hydrologic budget. Evapotranspiration involves the process of evaporation from open bodies of water, wetlands, snow cover, and bare soil and the process of transpiration from vegetation. The principal climatic factors influencing evapotranspiration are solar radiation and wind speed. In the conterminous United States, evapotranspiration averages about 67 percent of the average annual precipitation and ranges from 40 percent of the precipitation in the Northwest and Northeast to about 100 percent of the precipitation in the Southwest.

Estimates of the mean annual evapotranspiration have been derived from hydrologic budgets for each State. These estimates indicate that statewide evapotranspiration within the conterminous United States ranges from about 10 inches per year in the semiarid Southwest to about 35 inches per year in the humid Southeast. However, in selected areas of the Southwest where moisture is available and solar radiation is high, evapotranspiration rates in saltcedar have been estimated to be about 56 inches per year.

Seasonal trends in evapotranspiration follow the seasonal trends in air temperature-maximum rates occur during the summer months, and minimum rates during the winter months. Advanced Very High Resolution Radiometer instruments installed on polar-orbiting satellites provide relative measurements of plant vigor, density of vegetation cover, and the seasonal duration of vegetation growth. These measurements also have been used to monitor the spatial and temporal persistence of drought for large areas.

Changes in evapotranspiration during a drought depend largely on the availability of moisture at the onset of a drought and the severity and duration of a drought. Evaporation from open bodies of water during a drought increases, but transpiration by plants, particularly shallow-rooted plants, generally decreases.

To effectively manage the Nation's water resources, water managers need to understand the significance of evapotranspiration in the hydrologic budget. Knowledge of the regional and seasonal variability of evapotranspiration and its change during a drought also is important.

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